

Clues from the prompt emission of GRB 080319B

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ABSTRACT

The extremely bright optical flash that accompanied GRB 080319B suggested, at first glance, that the prompt γ -rays in this burst were produced by Synchrotron self Compton (SSC). We analyze here the observed optical and γ spectrum. We find that the very strong optical emission poses, due to self absorption, very strong constraints on the emission processes and put the origin of the optical emission at a very large radius, almost inconsistent with internal shock. Alternatively it requires a very large random Lorentz factor for the electrons. We find that SSC could not have produced the prompt γ -rays. We also show that the optical emission and the γ rays could not have been produced by synchrotron emission from two populations of electron within the same emitting region. Thus we must conclude that the optical and the γ -rays were produced in different physical regions. A possible interpretation of the observations is that the γ -rays arose from internal shocks but the optical flash resulted from external shock emission. This would have been consistent with the few seconds delay observed between the optical and γ -rays signals.

Key words: gamma rays: bursts—radiation mechanism: nonthermal

1 INTRODUCTION

The radiation mechanism for the γ -ray burst (GRB) afterglow is widely accepted as synchrotron emission (see Piran 2004, for a review). However, the mechanism for the prompt emission is still uncertain. Most recently, Kumar & McMahon (2008) showed the inconsistency with the overall synchrotron model. On the other hand Piran, Sari & Zou (2008) found that Synchrotron self-Compton (SSC) cannot explain the prompt emission unless the prompt optical emission is very high. With a naked eye (5th magnitude) optical flash (Cwiok et al. 2008; Karpov et al. 2008) GRB 080319B (Racusin et al. 2008b), was a natural candidate for SSC (Kumar & Panaitescu 2008).

GRB 080319B was located at redshift $z = 0.937$ (Vreeswijk et al. 2008). Its duration T_{90} was ~ 57 s. The peak flux is $F_p \sim 2.26 \pm 0.21 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1}$ and the peak of the νF_ν spectrum $E_p \simeq 675 \pm 22 \text{ keV}$ (i.e., $\nu_p \sim 1.6 \times 10^{20} \text{ Hz}$, and consequently $F_{\nu,p} \sim 1.4 \times 10^{-25} \text{ erg cm}^{-2} \text{ Hz}^{-1} \text{ s}^{-1}$). The photon indexes below and above E_p are $-0.855^{+0.014}_{-0.013}$ and $-3.59^{+0.32}_{-0.62}$ respectively (Racusin et al. 2008). Choosing standard cosmological parameters $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, GRB 080319B had a peak luminosity $L_p \sim 9.67 \times 10^{52} \text{ erg s}^{-1}$ and an isotropic equivalent energy $E_{\gamma,\text{iso}} \simeq 1.32 \times 10^{54} \text{ erg}$ (Golenetskii et al. 2008).

The optical observations were going on even before the onset of the GRB because TORTORA was monitoring the same region

of sky at that moment. Karpov et al. (2008) reported the optical V-band light curve in the prompt phase (from ~ -10 s to ~ 100 s). Variability was evident and there were at least 3 or 4 pulses in the optical light curve. The peak V-band magnitude reached 5.3, corresponding to a flux density $\sim 28.7 \text{ Jy}$.

Models for the optical emission accompanying the prompt γ -rays have been extensively discussed since the early work of Katz (1994) who used a low energy spectrum $F_\nu \propto \nu^{1/3}$ and found that the prompt optical emission could be bright to 18th mag. The observations of a prompt strong optical flash from GRB 990123 Akerlof et al. (1999) lead to a wave of interest in this phenomenon. The t^{-2} decline of the early optical flash favored a reverse shock model (Sari & Piran 1999; Mészáros & Rees 1999) that was suggested just few month earlier (Sari & Piran 1999a). Optical emission from later internal shocks and residual internal shocks have been discussed by Wei et al. (2006) and Li & Waxman (2008) respectively, and the late internal shocks model has been used to interpret the optical flares detected in GRB 990123, GRB 041219a, GRB 050904 and GRB 060111B (Akerlof et al. 1999; Blake et al. 2005; Boër et al. 2006; Klotz 2006; Zou, Dai & Xu 2006). However, none of the previous bursts had the data as plentiful as that of GRB 080319B and the constraints on the models were not very tight.

The very strong optical flash of GRB 080319B lead naturally to the suggestion Kumar & Panaitescu (2008); Racusin et al. (2008) that internal shocks synchrotron produced the prompt optical emission while SSC produced the prompt γ -rays. We show here that self absorption of the optical poses major constraints on the source of the optical emission and we consider its implications

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on general models (including SSC) for the emission of this burst. The paper is structured as follows: In section 2 we consider the general constraints that arise from the optical emission. In section 4 we consider SSC model and in section 5 we make general remarks on Inverse Compton (IC). In section 6 we examine the possibility that the optical and γ -rays arose from two synchrotron emitting populations of electrons but in the same physical region. We find that the optical and the γ -rays were originated in physically different regimes. We discuss the implications of these results in section 6.

2 OPTICAL EMISSION

The very strong optical flash that accompanied GRB 080319B poses the strongest constraints on the emission mechanism. A lot can be learnt from studying this flash on its own. The observed optical signal, $F_{\nu, \text{opt}}$, must be less or equal than the corresponding black body emission:

$$F_{\nu, \text{opt}} \leq F_{BB} = 2(1+z)^3 \nu_{\text{opt}}^2 \Gamma \gamma_e m_e \left(\frac{R}{d_L} \right)^2 = 1.1 \times 10^{-24} \gamma_{e,2} R_{15}^2 \Gamma_3^2 \quad (1)$$

where m_e and q_e (that we use later) are the electron's rest mass and charge, Γ is the bulk Lorentz factor, γ_e is the typical electron Lorentz factor ($\gamma_e m_e c^2 \approx kT$), R is the emission radius, and d_L is the luminosity distance¹. This value should be compared with the observed optical flux $F_{\nu, \text{opt}} \sim 2.9 \times 10^{-22} \text{ erg cm}^{-2} \text{ Hz}^{-1} \text{ s}^{-1}$ which is more than two orders of magnitude larger than the one found for F_{BB} with "typical" values. This is the essence of the problem of finding a reasonable solution for the emission mechanism in GRB080319B. By itself this constraint imposes a rather large γ_e for reasonable values of R and Γ , or alternatively a very large value of R . It will be the major constraint over which models that we examine later fail.

This equation can be combined now with two expression that link R and Γ : The angular time scale:

$$\delta t > \frac{R}{2\Gamma^2 c}, \quad (2)$$

and the deceleration radius:

$$R < R_\gamma = \begin{cases} \frac{E}{4\pi A \Gamma^2 m_p c^2}, & \text{wind,} \\ \left(\frac{3E}{4\pi n \Gamma^2 m_p c^2} \right)^{1/3}, & \text{ISM,} \end{cases} \quad (3)$$

where m_p is the proton's mass, E is the energy of the outflow, n is the ISM density and A is the wind parameter.

Fig. 1 depicts the allowed region in the (Γ, R) phase space that satisfies all three constraints for either wind or ISM environments. One can see that the Black Body limit Eq. (1) pushes the emitting radius to large values. On the other hand the two other constraints limits R to small values. The allowed region is rather small and the radii are typically large and they won't be consistent with those needed for emitting the γ -rays. Note that the allowed region shrinks to zero if we take $\delta t \leq 0.1 \text{ sec}$ as implied from the γ -ray observations.

As the condition $R < R_\gamma$ applies for internal shocks, this result on its own limits strongly the ability of internal shocks to produce this optical flash. The only way out, within internal shocks is to increase γ_e to very large values. However, typical internal shocks

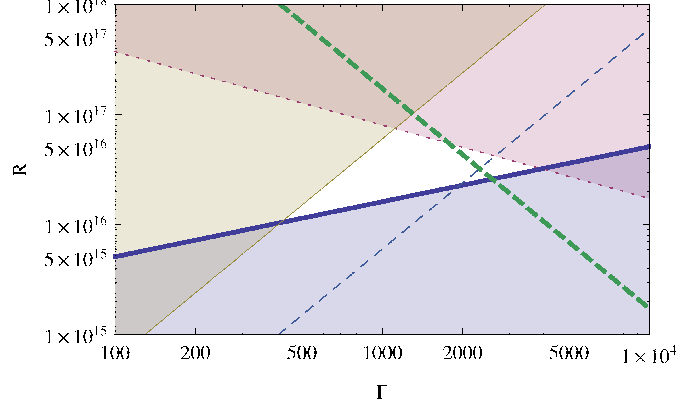


Figure 1. The parameter space in the (Γ, R) plane that satisfies the constraints Eqs. (1-3). The thick solid line is the black body constraint for $\gamma_e = 100$. The thin solid line indicates the variability time scale (for $\delta t_{\text{opt}} = 1 \text{ sec}$). Also shown (thin dashed line) is the variability constraint for $\delta t = 0.1 \text{ sec}$ corresponding to the γ -ray variability. The thin dotted line and the thick dashed line are the deceleration radius constraints for ISM and wind environments respectively. We choose conservatively $E = 10^{55} \text{ ergs}$, $n = 1 \text{ cm}^{-3}$, and $A = 3 \times 10^{33} \text{ cm}^{-1}$. The allowed regions for ISM with $\gamma_e = 100$ is the white triangle at the center. It increases slightly for a wind environment.

involve modest relativistic collisions in which such high Lorentz factors are not common (see however Kobayashi & Sari (2001)).

3 SYNCHROTRON SELF-COMPTON

We consider an SSC model with minimal assumptions. In fact unlike the previous section we don't use the inequalities (2) and (3) which depends on the overall model and we consider only the conditions within the emitting regions. The low energy (including optical) emission is produced by synchrotron and the γ -rays are the inverse Compton of this synchrotron emission by the same electrons. We assume that the emitting region is homogenous and it moves radially outwards with a relativistic Lorentz factor Γ towards us. It contains N_e electrons with a typical Lorentz factor γ_e . Slightly generalizing we allow for a filling factor f which implies that only a fraction f of the electrons are emitting synchrotron while all the electrons involved in IC. This can happen, for example if the magnetic field B occupies only a fraction f of the volume. As we see later this helps but does not yield a satisfactory solution.

We have four observables: $F_{\nu, \gamma}$, $F_{\nu, \text{opt}}$, ν_γ , ν_{opt} the fluxes and frequencies at the γ and the optical. We explore what are the conditions (N_e , B , Γ , γ_e and R) needed to produce the observations (see Piran, Sari & Zou (2008) for a related approach). As we assume that the γ -rays are produced by IC we have

$$Y \nu_L F_{\nu, L} = \nu_\gamma F_{\nu, \gamma} \quad (4)$$

and

$$\nu_\gamma = \gamma_e^2 \nu_L, \quad (5)$$

where $F_{\nu, L}$ and ν_L are the (unknown) peak flux and peak frequency of the low energy component (that is being Inverse Compton scattered to produce the soft γ), $Y = \gamma_e^2 \tau$ is the Compton parameter and τ is the optical depth for Thompson scattering. As the spectral shape is preserved by IC we can use the spectral indices below

¹ We denote by A_i the quantity $A/10^i$ in cgs units.

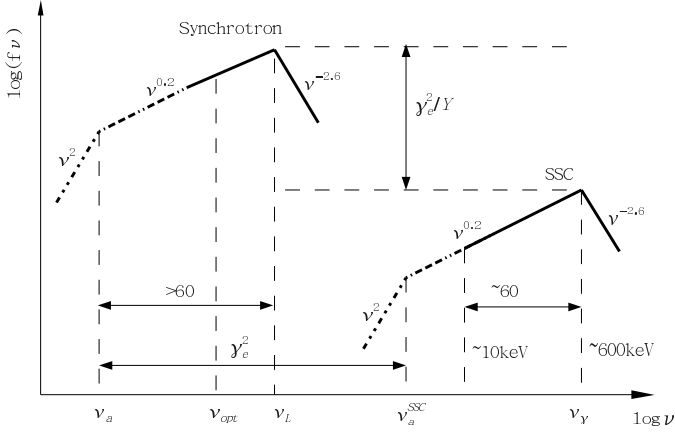


Figure 2. A schematic description of the spectrum in an SSC model. Note that if $10\text{keV}/\gamma_e^2 > \nu_{opt}$, that is if γ_e is small enough, ν_{opt} might be below ν_a and in this case Eq. (6) should be modified.

and above the peak γ -ray frequency ~ 0.2 and ~ -2.6 , respectively, to relate the optical flux and the flux at ν_L as²:

$$F_{\nu, opt} = F_{\nu, L} \left(\frac{\nu_{opt}}{\nu_L} \right)^\alpha, \quad (6)$$

where α is the observed index at the soft γ range. α will be either 0.2 or -2.6 depending on whether ν_L is larger or smaller than ν_{opt} (which we call UV and IR solutions respectively). The overall spectral distribution is shown in Fig. 2.

Combining these three equations we get:

$$\gamma_e = \left(\frac{Y F_{\nu, opt} \nu_{\gamma}^\alpha}{F_{\nu, \gamma} \nu_{opt}^\alpha} \right)^{\frac{1}{2(1+\alpha)}} = 530 \left(\frac{Y}{140} \right)^{\frac{1}{2(1+\alpha)}}. \quad (7)$$

We have $\gamma_e \sim 70Y^{0.4}$ for $\alpha = 0.2$ corresponding to a UV solution ($\nu_L > \nu_{opt}$) while for the IR solution ($\nu_L < \nu_{opt}$) $\alpha = -2.6$ and $\gamma_e \sim 2500Y^{-0.3}$.

Using this expression for γ_e we solve now the synchrotron frequency and peak synchrotron flux equations:

$$\nu_L = \frac{1}{(1+z)} \frac{3q_e}{2\pi m_e c} \Gamma B \gamma_e^2 \quad (8)$$

and

$$F_{\nu, L} = \frac{m_e c^2 \sigma_T}{3q_e} \frac{(1+z)}{4\pi d_L^2} \Gamma B f N_e. \quad (9)$$

Note that Γ and B appears as a product and hence we have two equations for two variables N_e and ΓB within the emitting region. Once we know N_e we can solve for R , using the optical depth $\tau = Y/\gamma_e^2$ and remembering $\tau = \sigma_T N_e / 4\pi R^2$:

$$R = \frac{1}{1+z} \sqrt{\frac{3d_L^2 q_e^2 F_{\nu, \gamma} \gamma_e^8}{2\pi c^3 f m_e^2 \nu_\gamma Y^2}} \approx 2 \times 10^{15} \frac{\gamma_{e,2}^4}{\sqrt{fY}}. \quad (10)$$

Turning now to the flux limit equation (1) we find

$$\frac{F_{BB}}{F_{\nu, opt}} = \frac{(1+z) 3q_e^2 F_{\nu, \gamma} \gamma_e^9 \nu_{opt}^2}{c^3 f F_{\nu, opt} \Gamma m_e \nu_\gamma Y^2} = 0.06 \frac{\gamma_{e,2}^9}{f \Gamma_3 Y^2}. \quad (11)$$

Substitution of the expression for γ_e in this equation yields for $\alpha = 0.2$:

$$\frac{F_{BB}}{F_{\nu, opt}} = 2 \times 10^{-3} \frac{Y^{1.75}}{f \Gamma_3}. \quad (12)$$

² Assuming that ν_L and ν_{opt} are in the same spectral regime. See subsequent discussion.

This ratio is not sensitive to the value of α used. It is clear that for reasonable values of Γ this ratio is less than unity unless Y is extremely large. This is the essence of the optical self-absorption problem that forbids any low Y SSC solution. A large Y will lead to a energy crisis where most of the energy of this (already very powerful) burst would have been emitted in the GeV regime leading to a huge overall energy requirement. Note that the isotropic equivalent γ -ray energy of this bursts is already larger than 10^{54} ergs.

Recalling that there is no obvious break in the γ -rays spectrum from the peak frequency $\sim 600\text{keV}$ down to $\sim 10\text{keV}$, a self absorption break should not appear in the range $[\nu_L/60, \nu_L]$. This sets an even more powerful constraint: $F_{BB}(\nu_L/60) > F_{\nu_L/60}$ which is typically significantly more difficult to satisfy (by ratio $(\nu_L/60\nu_{opt})^{2-\alpha}$ than Eq. (1).

We consider now briefly three caveats for the above result.

- (i) The filling factor f allows for a more reasonable solution. But one needs an extremely small f for a valid one.
- (ii) In a very small region of the parameter phase space, that is if $10\text{keV}/\gamma_e^2 > \nu_{opt}$ (see Fig. 2) an “optically thick” UV solution is possible. In this case F_ν increases like ν^2 from ν_{opt} to $\nu_L/60$. The solution is slightly different from the one given above (as Eq. (6) has to be modified) but qualitatively the results remains unchanged (see Fig. 2).
- (iii) For the IR solution ($\alpha = -2.6$), from Eq. (7) we find $\gamma_e \sim 3 \times 10^3$. This leads to a huge emission radius (see Eq. (10)) which is larger than $\sim 10^{20}$ cm and this solution can be easily ruled out.

4 GENERAL INVERSE COMPTON MODEL

So far we have considered an SSC solution. However, it is interesting to note that Eqs. (4-7) apply when the prompt γ -rays are the IC scattering of low energy external photons, provided that there is no significant relativistic bulk motion between the source of the seed photons and the IC electrons. For the UV solution, $\gamma_e \sim 50$ implies that the total kinetic energy should be much larger than the energy of the prompt γ -rays as the total internal energy of the electrons is much less than the rest mass energy of protons. This leads to a severe energy budget problem. For the IR solution ($\alpha = -2.6$) the Lorentz factor of the electrons is $\gamma_e \sim 2.5 \times 10^3 Y^{-0.31}$, then the peak of the low energy emission is at $\nu_L = 2.5 \times 10^{13} Y^{0.625}$ and the needed peak flux density (not necessarily synchrotron emission) is $F_{\nu_L} = 8.6 \times 10^{-19} Y^{-1.625} \text{erg cm}^{-2} \text{Hz}^{-1} \text{s}^{-1}$. Given the very small ν_L one can hardly satisfy $F_{\nu_L} \leq F_{BB}(\nu_L)$ (or even stronger $F_{\nu_L/60} \leq F_{BB}(\nu_L/60)$) for reasonable parameters.

5 TWO ELECTRON POPULATIONS

We consider now an alternative model in which the optical and the soft γ -rays arise from synchrotron emission from the same physical region but from different populations of electrons. We denote these populations with subscripts L and γ for the lower energy band and higher one respectively. γ and N are the typical Lorentz factor and the total number of electrons respectively of each kind. As we assume a single emitting region the magnetic field B and the bulk Lorentz factor Γ should be the same.

Using the peak synchrotron frequency relation $\nu_p \propto \gamma^2 \Gamma B$ and the peak flux density $F_{\nu, p} \propto N \Gamma B$:

$$\frac{\gamma_L^2}{\gamma_\gamma^2} = \frac{\nu_L}{\nu_\gamma}, \quad (13)$$

and

$$\frac{N_L}{N_\gamma} = \frac{F_{\nu,L}}{F_{\nu,\gamma}} \quad (14)$$

The total isotropic internal energy should be $\propto N_e \gamma$. Combining the above two equations, we obtain:

$$\frac{\gamma_L N_L}{\gamma_\gamma N_\gamma} = \frac{\nu_L^{1/2} F_{\nu,L}}{\nu_\gamma^{1/2} F_{\nu,\gamma}} = \frac{\nu_{opt}^{1/2} F_{\nu,opt}}{\nu_\gamma^{1/2} F_{\nu,\gamma}} \left(\frac{\nu_L}{\nu_{opt}} \right)^{1/2+\tilde{\alpha}}, \quad (15)$$

where $\tilde{\alpha}$ is the spectral slope in the range $[\nu_{opt}, \nu_L]$. If $\nu_L > \nu_{opt}$, then clearly $(\nu_L/\nu_{opt})^{1/2+\tilde{\alpha}} > 1$. On the other hand, if $\nu_L < \nu_{opt}$, $\tilde{\alpha} < -1$ and again $(\nu_L/\nu_{opt})^{1/2+\tilde{\alpha}} > 1$. Using the observed values we obtain:

$$\frac{\gamma_L N_L}{\gamma_\gamma N_\gamma} \geq \frac{\nu_{opt}^{1/2} F_{\nu,opt}}{\nu_H^{1/2} F_{\nu,\gamma}} \sim 4. \quad (16)$$

Thus a peculiar condition of this model is that the energy of the lower energy electron population that is responsible for producing the (relatively weak) optical signal exceeds that of the γ -rays producing component. Once more we are faced with an energy budget problem that makes the two synchrotron components model quite unlikely (see also Mochkovitch (2008)).

6 CONCLUSIONS AND DISCUSSIONS

Piran, Sari & Zou (2008) have shown recently that typical GRBs with normal (weaker than 12th magnitude) prompt optical emission cannot be produced by SSC of a softer component. The unique burst GRB 080319B had a very luminous prompt optical emission and one could expect, at first glance that the prompt γ -rays were produced in SSC of the optical prompt emission. This was the accepted interpretation in the discovery paper (Racusin et al. 2008) as well as in several others (Kumar & Panaitescu 2008; Fan & Piran 2008). The numerous detailed observations of this burst led to the hope that one can determine the physical parameters within the emitting regions here. However, a careful analysis reveals a drastically different picture. There is no reasonable SSC solution. One can make an even stronger statement and argue that it is unlikely that the prompt γ -rays are produced by inverse Compton scattering of seed photons produced by a source with no relativistic bulk motion relative to the IC electrons (regardless of the origin of the seed photons).

We also considered a situation with two populations of electrons that co-exist in the same emitting region. Both populations emit synchrotron radiation with the less energetic electrons producing the optical while the more energetic ones produce the γ -rays. We have shown that even though the total energy released in the optical is orders of magnitude lower than the energy released in γ -rays the lower energy electrons population should carry more energy - making, once more, the model energetically inefficient.

Combining these two results we conclude that the optical emission and the soft γ -rays do not come from a single origin. This is the main conclusion of this letter. Once we relax the condition that both modes of prompt emission are produced in the same region, there are many possibilities. However, even here the limits obtained in section 2 indicate that the optical emission is produced at a very large radius which is most likely incompatible with internal shocks (Note that typical internal shocks will have a rather modest values of γ_e). This raises the possibility that the optical emission is produced in this burst by the early external shock (possibly by the reverse shock). While there are several problems with this model

(in particular the fast rise of the optical emission that is faster than expected in this case Nakar & Piran (2004)) they are less severe than those basic issues that arise with the internal shocks. The fact that the optical emission follows to some extent the γ -rays but with a time delay of several seconds (Guidorzi 2008) is consistent with this model.

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REFERENCES

- Akerlof C. et al., 1999, *Nature*, 398, 400
- Blake C. H., et al., 2005, *Nature*, 435, 181
- Boër M., et al., 2006, *ApJ*, 638, L71
- Cwiok M., et al., 2008, *GCN circular*, 7445
- Fan Y. Z., & Piran T., 2008, *Front. Phys. Chin.*, 3, 306 (arXiv:0805.2221)
- Golenetskii, S., et al., 2008, *GCN, circular*, 7482
- Guidorzi C., 2008, private communication
- Karpov S., et al., 2008, *GCN Circular* 7502
- Katz J. Z., 1994, *ApJ*, 432, L107
- Klotz A., et al., 2006, *A&A*, 451, L39
- Kobayashi S., & Sari R., 2001, *ApJ*, 551, 934
- Kumar P., & McMahon, E., 2008, *MNRAS*, 384, 33
- Kumar P., & Panaitescu, A., 2008, arXiv:0805.0144
- Li, Z., Waxman, E., 2008, *ApJ*, 674, L65
- Mészáros P., & Rees M. J., 1999, *MNRAS*, 306, L39
- Mochkovitch, R., et al., 2008 in preparation
- Nakar E., & Piran T., 2004, *MNRAS*, 353, 647
- Piran T., 2004, *Rev. Mod. Phys.*, 76, 1143
- Piran T., Sari R., & Zou Y. C., 2008, arXiv:0807.3954
- Racusin J., et al., 2008b, *GCN circular*, 7427
- Racusin J. L., et al., 2008, *Nature*, 455, 183
- Sari R., & Piran T., 1999a, *ApJ*, 520, 641
- Sari R., & Piran T., 1999, *ApJ*, 517, L109
- Vreeswijk P. M., et al., 2008, *GCN circular*, 7444
- Wei D. M., Yan T., Fan, Y. Z. 2006, *ApJ*, 636, L69
- Zou Y. C., Dai Z. G., & Xu D., 2006, *ApJ*, 646, 1098